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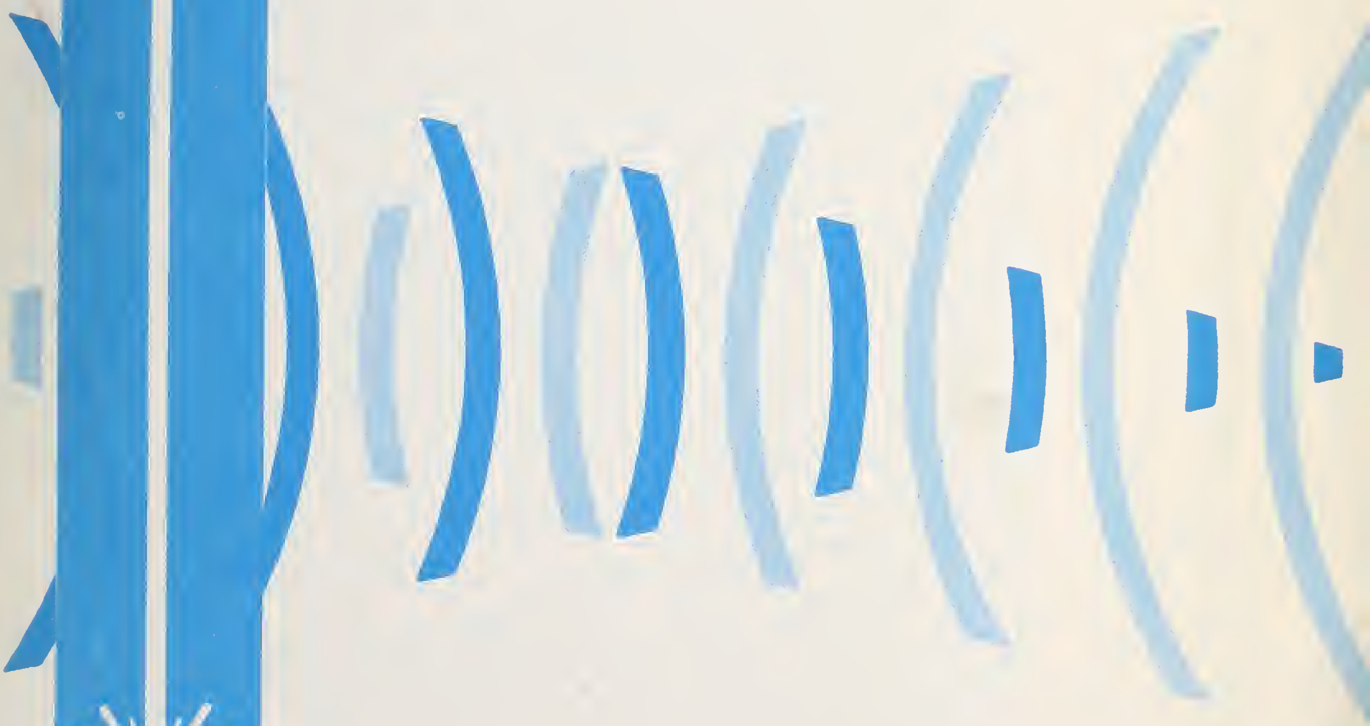
A COMPARISON of INSTRUMENT PERFORMANCE in MEASURING X-RAY TUBE CURRENT and mAs



U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION

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A COMPARISON of INSTRUMENT PERFORMANCE in MEASURING X-RAY TUBE CURRENT and mAs

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Division of Electronic Products

August 1975

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION
U.S Bureau of Radiological Health
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FOREWORD

The Bureau of Radiological Health conducts a national program to limit man's exposure to ionizing and nonionizing radiations. To this end, the Bureau (1) develops criteria and recommends standards for safe limits of radiation exposure, (2) develops methods and techniques for controlling radiation exposure, (3) plans and conducts research to determine health effects of radiation exposure, (4) provides technical assistance to agencies responsible for radiological health control programs, and (5) conducts an electronic product radiation control program to protect the public health and safety.

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Readers are encouraged to report errors or omissions to the Bureau. Your comments or requests for further information are also solicited.

John C Villforth

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

The Bureau of Radiological Health's Division of Electronic Products is responsible for the development of test procedures and test instrumentation required for the enforcement of the diagnostic x-ray equipment performance standard promulgated under the Radiation Control for Health and Safety Act of 1968. Among the tests performed in the enforcement of the standard is the measurement of either x-ray tube current in milliamperes and exposure time in seconds, or the product of tube current and exposure time in milliampere-seconds.

This report describes two commercially available, noninvasive, large-aperture current probe systems and describes their suitability for making tube current measurements as specified under the Radiation Control for Health and Safety Act of 1968.

Technical contributions were made by Thomas R. Lee and Ray L. Walchle, and artwork was furnished by Dean F. Elbert.

Roger H. Schneider

Roger H. Schneider
Director
Division of Electronic Products

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ABSTRACT

The Bureau of Radiological Health has evaluated two commercially available, noninvasive, large-aperature current probe systems for suitability in the measurement of x-ray tube current and x-ray tube current-time product as required in the enforcement of the Federal performance standard for diagnostic x-ray equipment. The response of the two systems to typical x-ray tube current waveforms is investigated and compared to the response necessary for good accuracy over the range of expected exposure times and tube currents.

The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health, Education, and Welfare, Public Health Service.

A COMPARISON OF INSTRUMENT PERFORMANCE IN MEASURING X-RAY TUBE CURRENT AND mAs

1. INTRODUCTION

The Federal performance standard for diagnostic x-ray equipment, promulgated under the Radiation Control for Health and Safety Act of 1968, requires manufacturers of x-ray systems to specify and assure the accuracy of certain critical x-ray tube operating parameters. Among these parameters (or "technique factors") are either x-ray tube current in milliamperes (mA) and exposure time in seconds or the product of tube current and exposure time in milliampere-seconds (mAs). The standard specifies that the technique factors must be visually indicated on the x-ray machine control panel and that the deviation of the actual technique factors from the indicated values shall not exceed the limits given by the manufacturer in his specifications.

This report describes two instruments, each commercially available, which are capable of measuring x-ray tube current in a noninvasive manner; i.e. they can be used without disconnecting any high-voltage cables or making any other electrical connection to the x-ray machine. The performance of the two instruments is compared and the limitations of each are noted. Finally, a modification to improve the performance of one of the instruments is proposed.

2. SIMPLIFIED OPERATION OF A TYPICAL X-RAY MACHINE

A typical single-phase full-wave rectified x-ray machine consists of a control panel, a high-voltage generator, and an x-ray tubehead connected as shown in figure 1. Switch 1 (SW1) controls the exposure time by controlling the time a.c. voltage is applied to the primary of the high-voltage transformer. The tube current is controlled by regulating the temperature of the cathode, which is heated by an adjacent filament. The filament current is controlled by the "mA adjust" autotransformer. The cathode supplies electrons by thermionic emission. The high potential difference maintained between the cathode and a metallic target (anode) accelerates the electrons toward the target. The anode face is at an angle (15-20 degrees) relative to the electron beam. The x rays that emerge from the target pass through an aperture (port) in the side of the tube.

The electron beam current is defined to be the x-ray tube current.

3. MEASUREMENT OF X-RAY TUBE CURRENT

X-ray tube current is presently measured in any one of three ways (figure 1): (1) by insertion of a rectified d.c. milliammeter into the ground lead of the high-voltage transformer; (2) by insertion of an insulated d.c. milliammeter

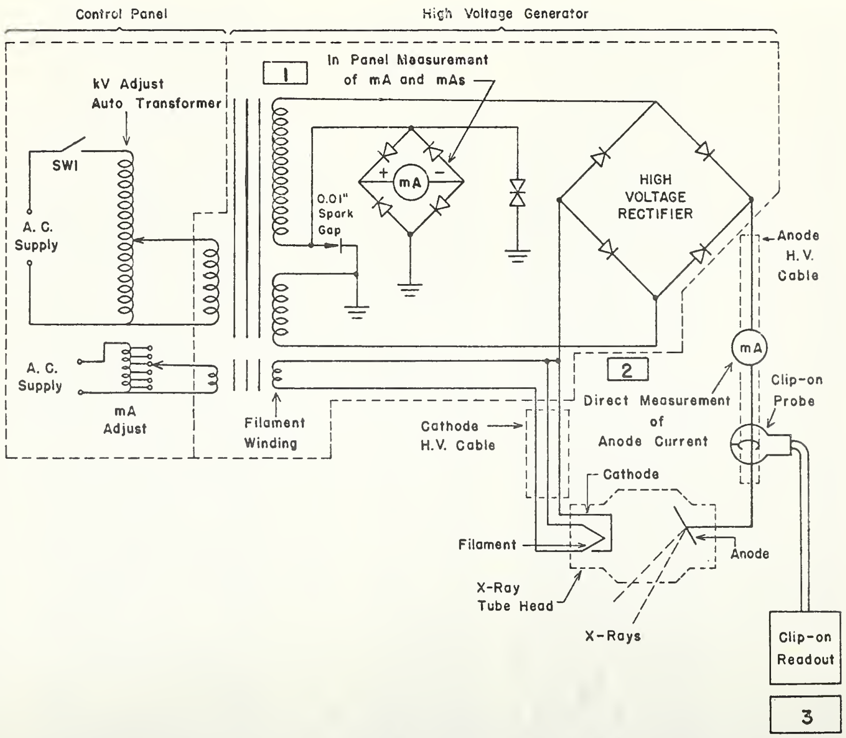


Figure 1. Schematic Diagram of a Simplified X-Ray Machine.

directly into the x-ray tube anode circuit; or (3) by placing a magnetically sensitive probe in close proximity to the high-voltage cable to the x-ray tube anode (a noninvasive current measurement).

The first two approaches to tube current measurement are undesirable from an inspection point of view because both require the disruption of the x-ray machine wiring. The third approach involves the use of an instrument with a large aperture probe which is clamped around the anode cable. The two major commercial suppliers of this type of noninvasive instrument are Hewlett Packard and Tektronix. The Hewlett Packard instrument is the Model 428B Clip-on Milliammeter with Model 3528A Large Aperture Current Probe; the Tektronix instrument is the Model P6042 Current Probe with Model CT-5 Large Aperture Clip-on Current Transformer. The two instruments are comparable in price.

4. TYPICAL CURRENT WAVEFORMS

The x-ray machine shown in figure 1 is a full-wave rectified type. The actual tube current of a full-wave rectified machine is shown in figure 2b. Other common types of x-ray machines employ either half-wave rectified generators (figure 2a), or forced commutator three-phase generators (figure 2c).

Exposure time is defined to be the time during which current flows. The current-time product Q in mAs is mathematically defined as:

$$Q = \int_{t_1}^{t_2} i(t)dt \qquad (1)$$

where $t_2 - t_1$ is the exposure time and i(t) is the current as a function of time.

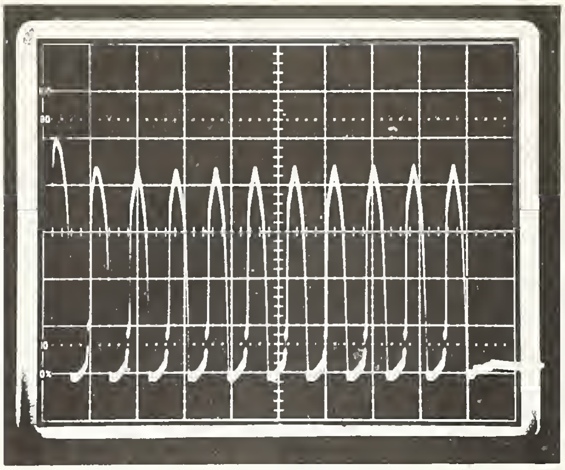
The average tube current, I_{ave}, is determined by the following relation:

$$I_{ave} = \frac{Q}{t_2 - t_1} \qquad (2)$$

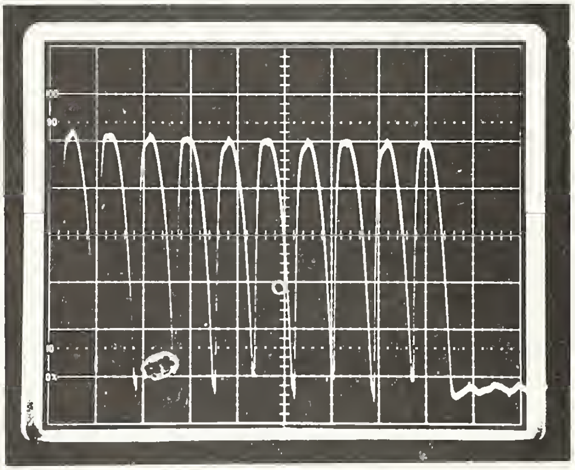
Typical exposure times range from 1/120 second to 6 seconds for full-wave and half-wave rectified machines and from 1 millisecond to 6 seconds for three-phase machines. Typical tube currents vary from 10 mA to 300 mA for half-wave and full-wave rectified machines and from 25 mA to 1500 mA for three-phase machines.

5. DESIRED CHARACTERISTICS OF A CLIP-ON MILLIAMMETER

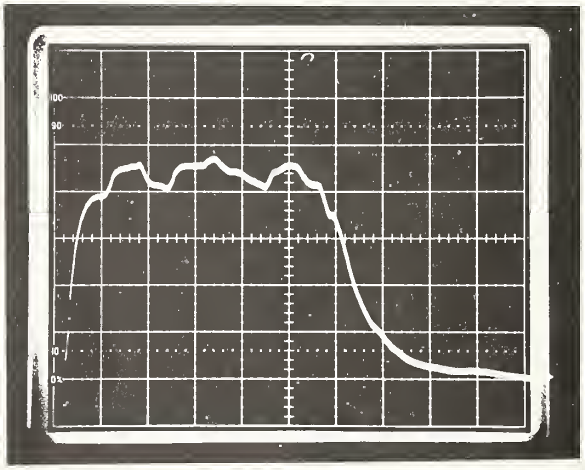
An ideal clip-on milliammeter (COMA) will pass all frequencies present in the power spectrum of the signal to be measured. This ideal COMA would have an infinite bandwidth. The shortest current pulse normally encountered in diagnostic radiology is of 1 millisecond duration and is from a three-phase machine. A simplified model for this pulse is shown in figure 3a. The power spectrum of the pulse is shown in figure 3b. In actual practice, a device with a 3-dB bandwidth of 10 kHz (0 to 10 kHz) will pass greater than 99 percent of the power of the pulse shown in figure 3a and an even greater percentage for longer pulses.



2a. Single-phase dental x-ray machine.

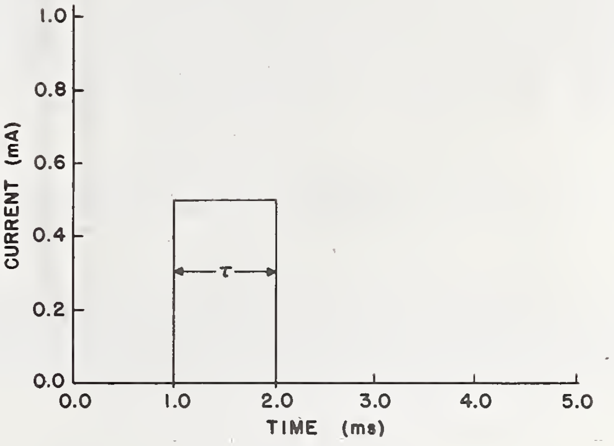


2b. Full-wave rectified machine.

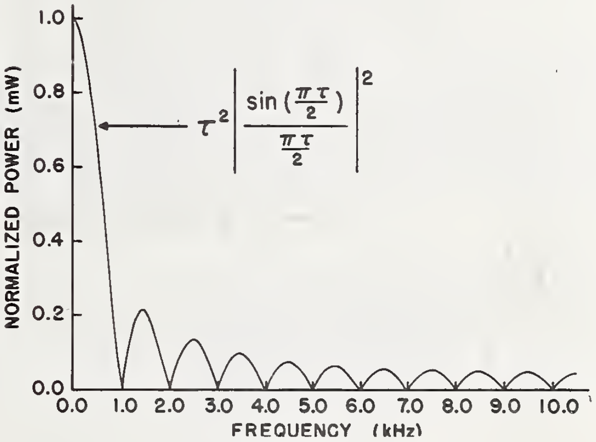


2c. Three-phase machine.

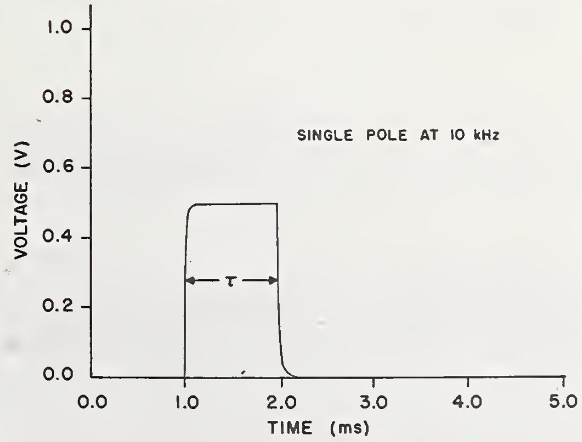
Figure 2. Typical Tube Current Waveforms.



3a. Input Pulse.



3b. Power Spectrum of Input Pulse.



3c. Output Pulse.

Figure 3. Pulse Response of a Satisfactory COMA.

If the COMA is modeled as a low-pass filter with a 10-kHz bandwidth and 6-dB/octave rolloff, the shortest expected pulse will be only slightly distorted (see figure 3c). A satisfactory COMA, therefore, would have the characteristics of a single-pole low-pass filter with a 10-kHz break frequency. Neither the Hewlett Packard nor the Tektronix probe have these characteristics. Results obtained for each of these probes are discussed in section 7.

6. COMPUTER SIMULATION OF PROBE RESPONSES

6.1 THEORY

To simplify the mathematical analysis, each probe has been modeled as a two-port linear network (see figure 4). For steady-state signals, the input current and output voltage are related by an equation of the form:

$$v_2(t) = h(t)*i_1(t) \tag{3}$$

$$v_2(t) = \int_{-\infty}^{\infty} h(t)i(t-\tau)d\tau \tag{4}$$

where $v_2(t)$ is the output voltage as a function of time, $h(t)$ is the characteristic impulse response of the two-port network, and $i_1(t)$ is the input current as a function of time. The output voltage $v_2(t)$ can be related to $h(t)$ and $i_1(t)$ by the convolution theorem, which is illustrated by equation (4). The Fourier transforms of each of the variables in equation (3) are:

$$H(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega t}h(t)dt \tag{5}$$

$$V_2(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega t}v_2(t)dt \tag{6}$$

$$I_1(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\omega t}i_1(t)dt \tag{7}$$

The convolution theorem *(1)* states that a convolution in the time domain becomes complex multiplication in the frequency domain. Therefore, using equations 5, 6, and 7, the following relation is found:

$$V_2(\omega) = H(\omega)I_1(\omega) \tag{8}$$

Equation 8 shows that if the transfer function $H(\omega)$ is known, only the transform of the input current $I_1(\omega)$ need be specified in order to determine the transform of the output voltage by multiplication. To find the output voltage in the time domain, it would be necessary to take the inverse Fourier transform of the right-hand side of equation (8).

As a first approach to the problem of determining exact frequency response, each probe was modeled as a simple low-pass or bandpass filter, using manufacturer's data for the break frequencies. H(ω) for the Hewlett Packard probe was assumed to be that of a low-pass filter with a 3-dB breakpoint at 400 Hz and a rolloff of 6 dB/octave. Comparison of the computer-predicted output with the measured output showed this approximation to be inadequate. A matching technique (see section 7) was then used to determine a more representative response. Using this matching technique, H(ω) was experimentally found to be:

$$H(\omega) = \frac{\omega_1^2}{(j\omega)^2+\alpha_1\omega_1 j\omega+\omega_1^2} \cdot \frac{\omega_2^2}{(j\omega)^2+\alpha_2\omega_2 j\omega+\omega_2^2} \qquad (9)$$

where $\omega_1/2\pi$ = 420 Hz, $\omega_2/2\pi$ = 1.65 kHz, α_1 = 3.06, and α_2 = 1.05.

H(ω) for the Tektronix probe was calculated by using the published characteristics from the operator's manual and was found to be:

$$H(\omega) = \frac{j\omega T_1}{(1+j\omega T_1)(1+j\omega T_2)} \qquad (10)$$

where $T_1 = 1/2\pi f_1$, f_1 = 0.5 Hz, and $T_2 = 1/2\pi f_2$, f_1 = 20 MHz.

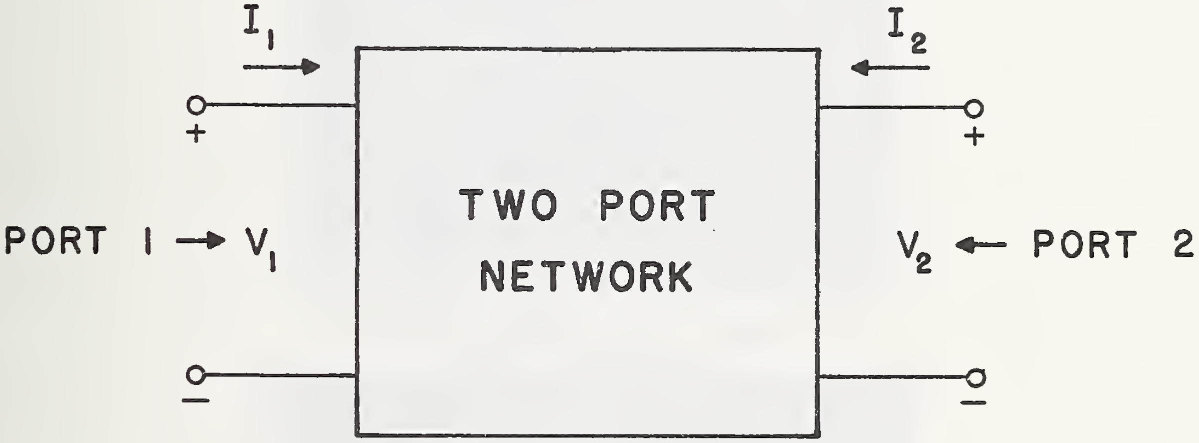
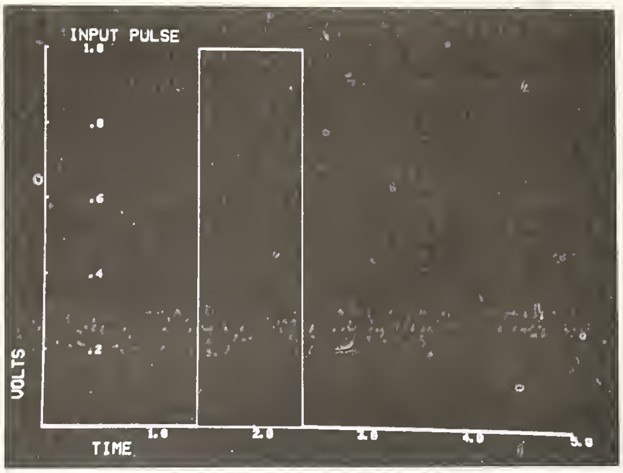


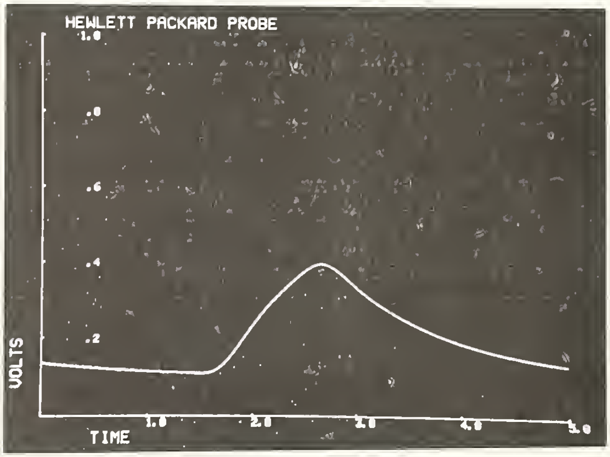
Figure 4. Two-Port Linear Model.

6.2 COMPUTER ANALYSIS OF PROBES

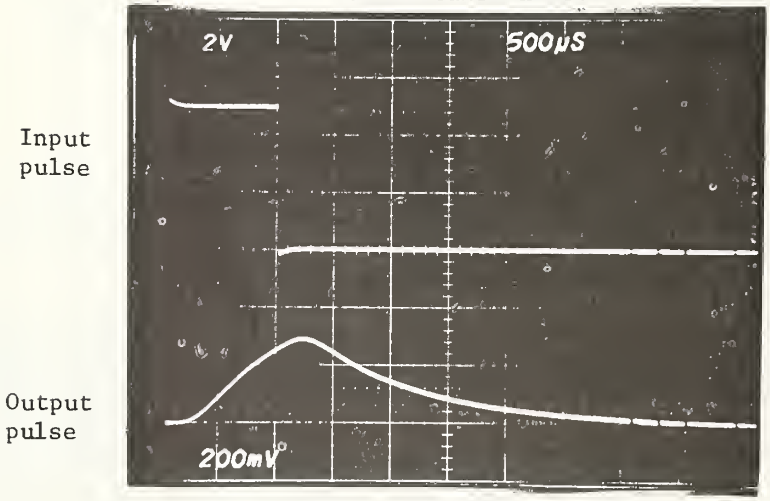
Using the techniques of the previous section, a computer program was written in Fortran and run on a Hewlett Packard 2100 computer (see appendix A) to determine the response of the probes to a pulse such as shown in figure 3a as well as to determine the effect the probes would have on the measurement of mAs. The program consists of two parts: (1) the main program and (2) the Fast Fourier transform subroutine (2) which is configured to compute the forward and inverse transforms. The input to the simulated probe is given as a voltage pulse, rather than a current pulse as discussed in the previous section. This was done to assure agreement between the scales of all the input and output pulses, as shown in figures 5 and 6. This poses no problem since the input current can be



5a. Input pulse (computer generated) time scale in ms.



5b. Output pulse (computer generated) time scale in ms.



5c. Actual instrument response.

Figure 5. Response of the Hewlett Packard Instrument.

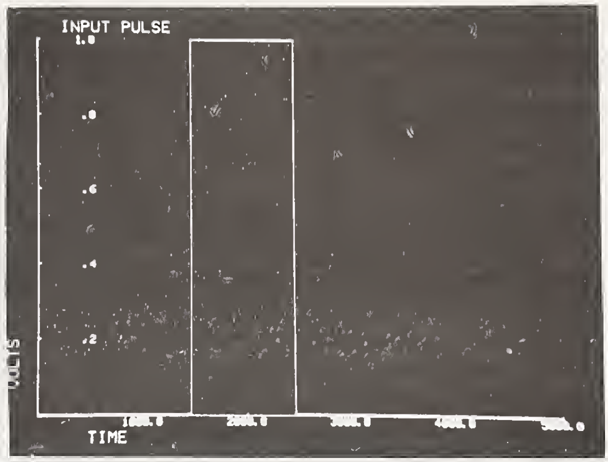


Figure 6a. Input pulse (computer generated) time scale in ms.

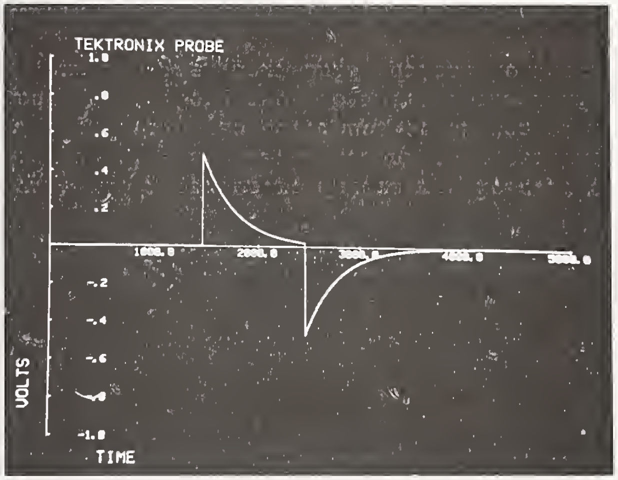


Figure 6b. Output pulse (computer generated) time scale in ms.

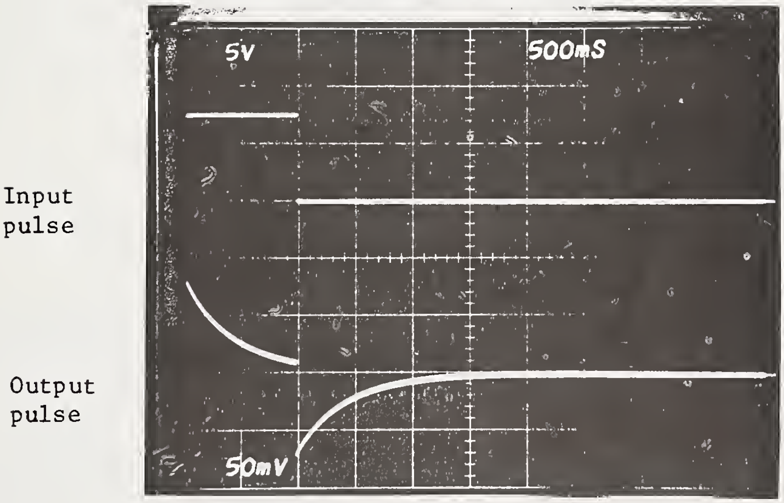


Figure 6c. Actual instrument response.

Figure 6. Response of the Tektronix Instrument.

derived from the input voltage by using the configuration shown in figure 7. Therefore, the frequency response can be determined for an input which is expressed as either a voltage or current pulse, since the difference is a simple scale factor, R. The main program places the desired input waveform, $v_1(t)$, into the array labeled A. The Fast Fourier transform subroutine is then called to take the forward transform of $v_1(t)$. When the subroutine is completed, $V_1(\omega)$ will have replaced $v_1(t)$ in the array A. The next step consists of multiplying the array A by the array G, which contains the transfer function of the particular instrument in question, and placing the result back in A. Upon completion of the multiplication step, the inverse Fast Fourier transform is performed on array A and the result is placed again into array A. The contents of A now represent the output waveform as a function of time. The contents of A are displayed on the cathode-ray display of the computer. Figure 5 shows the response of the Hewlett Packard Probe and figure 6 shows the Tektronix probe response. As can be seen, the computer results agree with the actual response, except for an offset, which indicates that the model used for both measurement systems was reasonable. The offset is due to the mathematics of Fourier analysis. The Fourier transform operates only on periodic signals. Therefore, the offset corresponds to the first term (d.c.) of the Fourier expansion of a pulse which has a 1-millisecond duration and a repetition frequency of 200 Hz. The full scale time of figure 5b (5 ms) corresponds to one period. (Note: figures 5c and 6c, as well as all subsequent oscilloscope photographs in the text, depict the response of the probe systems to electronically simulated tube current waveforms.)

The main program calculates the mAs of the input current pulse using equation (1). The mAs of the output current pulse is calculated by substituting $i_2(t)$ for $i(t)$ in equation (1), where $i_2(t) = v_2(t)/R$, $R = 1$ ohm. The analysis of the Hewlett Packard probe reveals that the mAs determination is not affected by the system: if the output of the Hewlett Packard system is integrated over the exposure time the correct mAs is calculated. Such is not the case for the Tektronix system. If the output of this system is integrated over the exposure time the result is incorrect: the longer the exposure time the larger the error.

By using a hand calculation method *(3)*, mAs may be determined with the Tektronix system. However, hand calculations assume ideal waveshapes (i.e.,

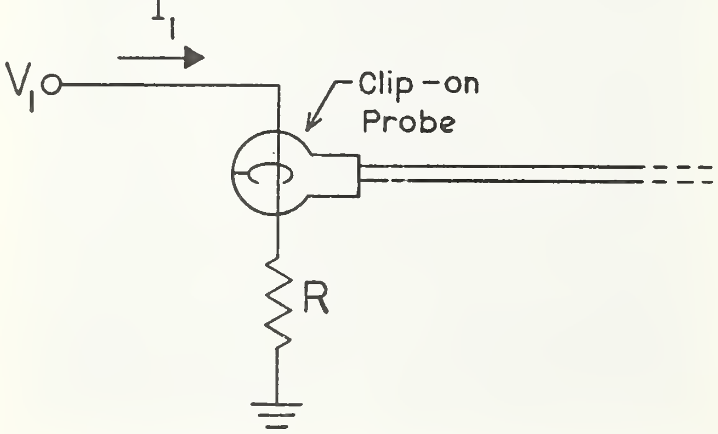


Figure 7. Circuit Used to Relate to $V_1(s)$ to $I_1(s)$.

rectangular pulses and pure sinuoidal rectified pulses), which seldom occur. High tube current or nonlinearities in the x-ray machine can cause large deviations from the ideal waveshape (see figure 2), resulting in a large error in the hand-calculated value of mAs.

7. HARDWARE SIMULATION OF PROBE RESPONSES

The transfer function of each of the two current probe systems was modeled using electronic filters in order to verify the response indicated by the manufacturer's specifications and to determine the feasibility of modifying the system response to more closely emulate the desired characteristics presented in section 5.

In section 6, $i_1(t)$ was treated as a periodic signal to satisfy the requirements of the Fourier transform. The more general case will be treated here by replacing $j\omega$ in equations (9) and (10) by s (the Laplace variable). In this manner, equations (11) and (12) become the Laplace transform of the characteristic impulse response.

Electronic models for the probe systems were examined in terms of the input and output voltages, where $H(s) = V_2(s)/V_1(s)$, since pulsed voltage sources are more readily available than pulsed current sources, and voltage signals are more easily measured on an oscilloscope than current signals. A resistor R relates $V_1(s)$ to $I_1(s)$ independent of frequency (see figure 7) so that the frequency response of the system can be uniquely determined from $V_1(s)$ and $V_2(s)$. (Note: In the theoretical analysis, R may be considered to be 1 ohm.)

The operator's manual for the Hewlett Packard model 428B specifies the passband of the instrument to be from d.c. to 400 Hz, with the response 3 dB down at 400 Hz. From this data, the system was modeled using a low-pass active filter with a 3 dB breakpoint at 400 Hz and a rolloff of 6 dB/octave. This filter provided neither sufficient high frequency attenuation nor sufficient phase shift to match the response of the model 428B. The Hewlett Packard response was thus shown to be more than that of a simple first order system.

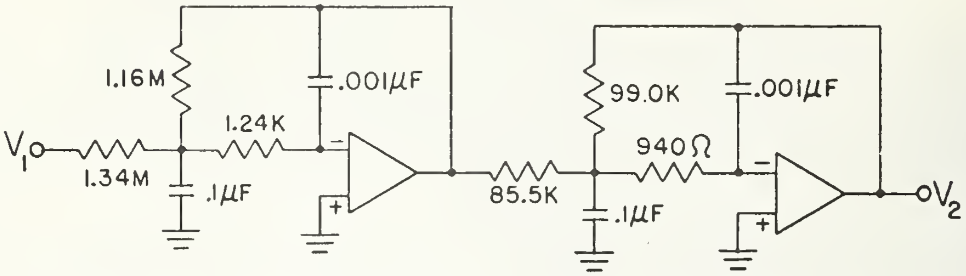
When an attempt was made to determine the order of the system response by measuring the attenuation at 4 kHz, the signal level was comparable to the noise level and an accurate measurement was not possible. The output phase, however, was fairly distinct even at very low amplitude levels, and total system phase shift at high frequencies was found to be 360 degrees, indicating a fourth order response.

A fourth order low-pass filter with a transfer function of the general form

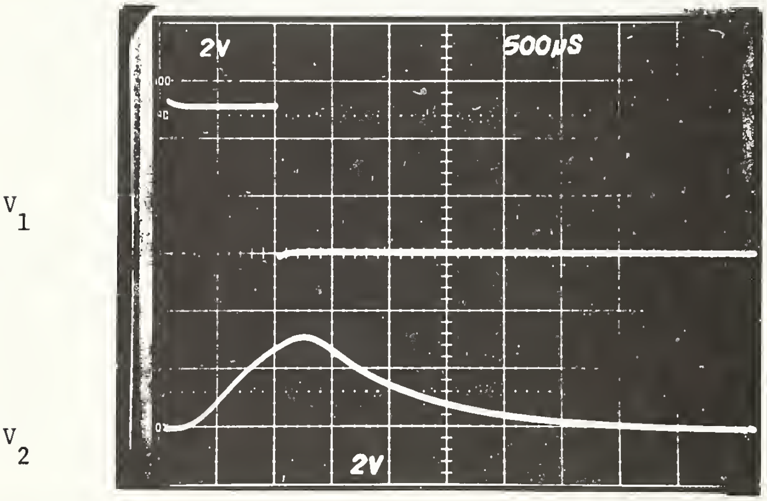
$$H(s) = \frac{\omega_1^2\omega_2^2}{(s^2+\alpha_1\omega_1 s+\omega_1^2)(s^2+\alpha_2\omega_2 s+\omega_2^2)} \tag{11}$$

was fabricated by cascading two second order filters as shown in figure 8a. Circuit components were selected on the assumption that $\omega_1/2\pi$ was approximately 400 Hz and that $\omega_2/2\pi$ was approximately 1 kHz. The parameters ω_1, α_1, ω_2, and α_2 were then tuned until the closest possible match to the actual amplitude and phase response of the Hewlett Packard system was achieved. Final network component values of the electronic model shown in figure 8a could then be used to determine the actual numerical values for ω_1, α_1, ω_2, and α_2, which appear in section 6.

Figure 8b shows the response of the electronic filter to a 1 millisecond pulse input. Agreement with the response of the Hewlett Packard probe as shown in figure 5c demonstrates the accuracy of the electronic model and the assumed system transfer function (equations 9 and 11).



8a. Schematic diagram.



8b. Response to a 1-msec pulse.

Figure 8. An Electronic Low-Pass Filter Which Approximates the Response of the Hewlett Packard Instrument.

Departure of the Hewlett Packard probe from the theoretical model occurred at high frequencies because of the nature of the system. Since the Model 428B chops the magnetic field at a 40-kHz rate in order to obtain response to d.c., harmonics of the chop frequency cause large amplitude errors in the output (beat frequencies down as little as 3 dB at 40 kHz). Since the power spectrum for the worst case input (1-millisecond pulse) contains little power above 10 kHz, the effects of the chop frequency can be expected to contribute little error to a typical measurement.

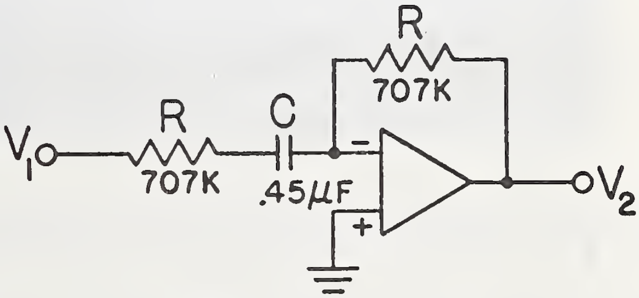
The operator's manual for the Tektronix model CT-5 current transformer specifies the 3-dB bandwidth of the combined P6042-CT-5 system to be 0.5 Hz to 20 MHz. The system could be modeled as a bandpass filter with 3-dB breakpoints at 0.5 Hz and 20 MHz, with 6-dB/octave rolloff outside the passband; however, since the upper breakpoint exceeds the 10-kHz figure of section 5 by such a wide margin, its effects can be neglected in this application, and the system can be modeled as a high-pass filter with a 0.5-Hz breakpoint and 6-dB/octave rolloff.

In general the transfer function of a first order high-pass filter is given as

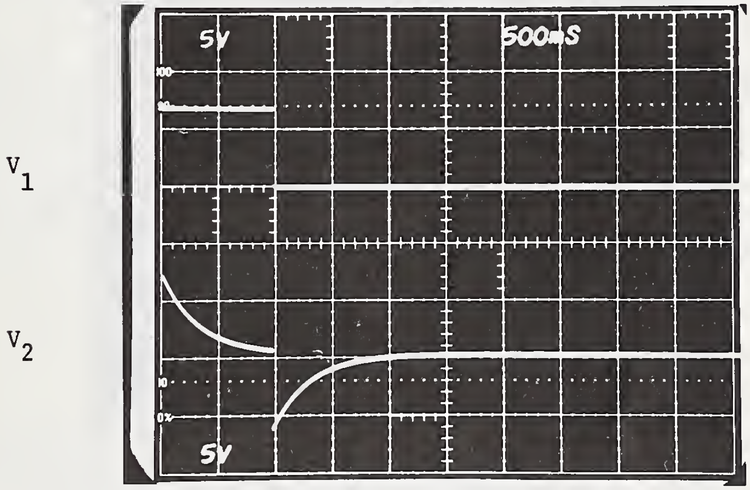
$$H(s) = \frac{T_1 s}{1+T_1 s} \tag{12}$$

For the Tektronix system, $T_1 = 1/2\pi f_1$ as described in section 6. An electronic filter having this transfer function was fabricated as shown in figure 9a. Figure 9b shows the response of the filter to a 1-second input pulse, and comparison with the response of the Tektronix system as shown in figure 6c demonstrates the validity of the model.

Departure of the Tektronix probe from the theoretical model was minimal. The sample P6042-CT-5 investigated had a breakpoint at 0.354 Hz rather than at 0.5 Hz. The difference could have resulted from statistical variations arising in the manufacturing process of the CT-5 current transformer or conservative specification by the manufacturer. Nonetheless, the improvement over the theoretical response is not sufficient for significant improvement in system performance at very low frequencies.



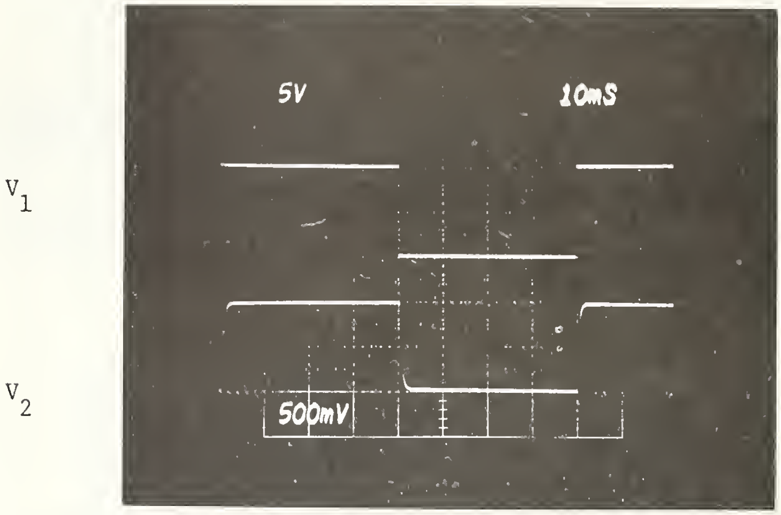
9a. Schematic Diagram.



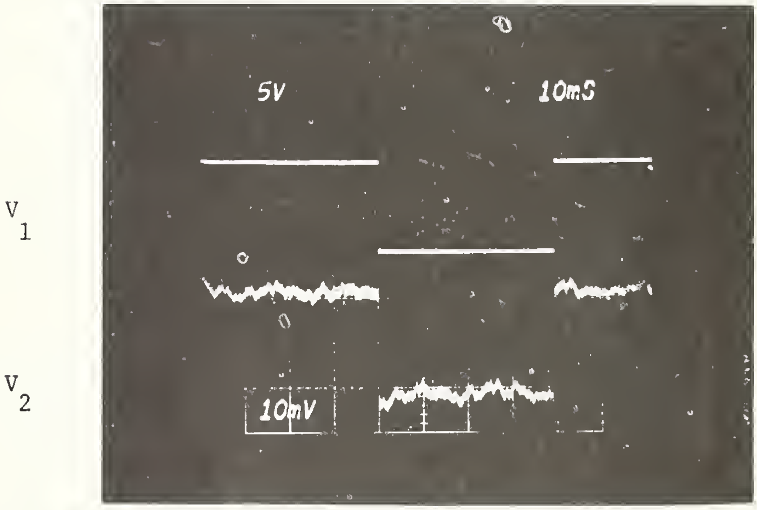
9b. Response to a 1-sec pulse.

Figure 9. An Electronic High-Pass Filter Which Approximates the Response of the Tektronix Instrument.

One characteristic of current probe performance not easily simulated is resolution. In measurements pertaining to frequency response, input signals of sufficient amplitude to provide easily measurable output signals were used (R in figure 7 was 100 ohms). Resolution, however, was evaluated using a 10-mA input pulse, and the results appear in figure 10.



10a. Response of the Hewlett Packard Instrument.



10b. Response of the Tektronix Instrument.

Figure 10. Response of Probe Systems to 10-mA Pulses
(R in Figure 7 is 1 kilohm).

8. PROBE MODIFICATIONS FOR IMPROVED PERFORMANCE

It has been shown in previous sections that neither the Hewlett Packard nor the Tektronix current probe system has the d.c. to 10-kHz frequency response desirable for performing accurate measurements over the entire 1-millisecond to 6-second range of exposure times. Simple methods of frequency compensation to extend the passband of the Hewlett Packard probe to 10 kHz and that of the Tektronix probe to d.c. were investigated.

Extension of the passband of the Hewlett Packard probe cannot be made without extensive modification to the system electronics. Errors resulting from the chop frequency, as examined in section 7, would be greatly enhanced by compensation for high-frequency rolloff. Thus, no simple improvement to the Hewlett Packard system is considered feasible.

Compensation for low-frequency rolloff of the Tektronix probe system can be provided with relative simplicity. When a circuit having the transfer function

$$H(s) = \frac{1 + T_1 s}{T_1 s} = \frac{1}{T_1 s} + 1 \tag{13}$$

is placed in series with the Tektronix P6042 output, the resulting response is

$$H(s) = \frac{T_1 s}{(1+T_1 s)(1+T_2 s)} \cdot \frac{1+T_1 s}{T_1 s} = \frac{1}{1+T_2 s} \tag{14}$$

As this combination has no rolloff until well beyond 10 kHz ($T_2 = 1/(2\pi \cdot 20\ \text{MHz})$), the Tektronix system, modified in this manner, could more than satisfy the frequency response requirements presented in section 5.

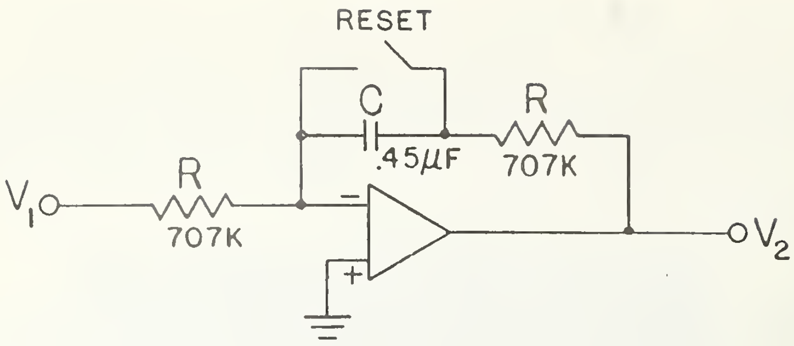
Figure 11a shows an electronic filter having the transfer function given by equation 13. The response of the Tektronix P6042-CT-5 to a 10-second pulse is shown in figure 11b. When compensated by the circuit of figure 11a, the response of the system to a 10-second pulse is as shown in figure 11c.

Practical problems with this approach are greatly outweighed by the value of restored d.c. response. In practice, R_f (see appendix C) must be adjusted to match the breakpoint of the compensation circuit with that of the probe in use, and R_1 must be adjusted to preserve the original gain of the compensator. C must be discharged periodically due to voltage offsets in the circuitry, and the d.c. output level of the P6042 must be carefully adjusted to zero. The slight negative drift appearing in figure 11c is the result of a small d.c. level at the output of the P6042.

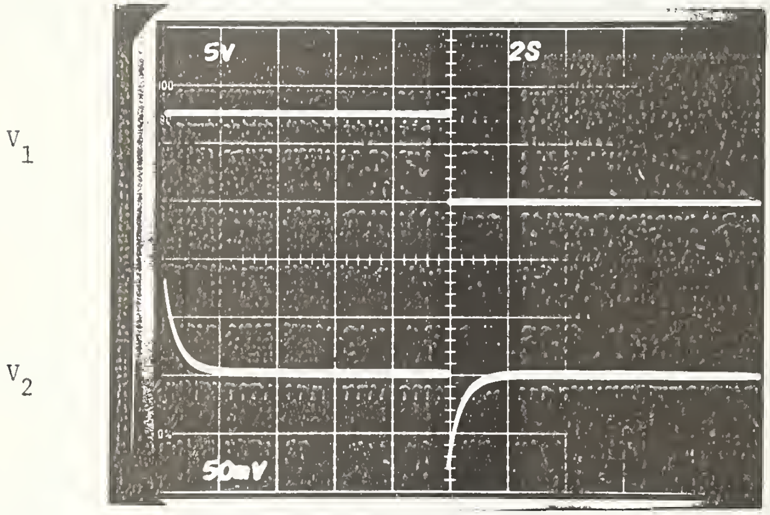
9. CONCLUSIONS

Two noninvasive current measurement systems were examined for suitability in measuring x-ray tube current and mAs over the range of conditions encountered in the enforcement of standards promulgated under the Radiation Control for Health and Safety Act of 1968. Performance requirements for accurate measurements were formulated, and the instruments were evaluated in light of these requirements, both with models and actual hardware.

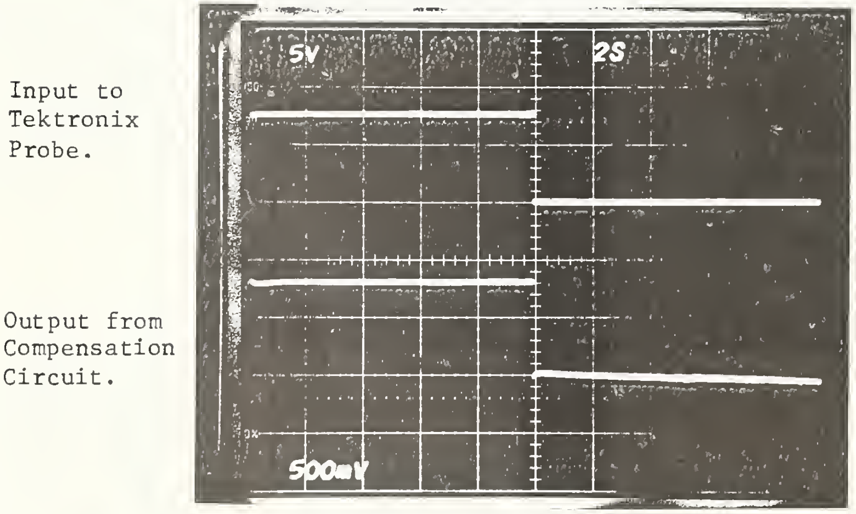
The Hewlett Packard Model 428B Clip-on Milliammeter with Model 3528A Large Aperature Current Probe was found to be deficient in the measurement of short current pulses (1 msec to 100 msec); however, very accurate measurements of mAs



11a. Schematic Diagram of a Circuit Which Compensates for the Low-Frequency Rolloff of the Tektronix Instrument.



11b. Response of the Tektronix Instrument to a 10-sec Pulse.



11c. Response of the Tektronix Instrument with Low-Frequency Compensation to a 10-sec Pulse.

Figure 11. Low-Frequency Compensation for the Tektronix Instrument.

can be performed for exposures as short as 1 millisecond in duration. Resolution was found to be adequate for good accuracy when currents are as low as 10 mA. No improvement in system performance was deemed feasible without extensive modification.

The Tektronix Model P6042 Current Probe with Model CT-5 Large Aperature Clip-on Current Transformer was found to be deficient in the measurement of current and mAs for exposures greater than 100 milliseconds in duration. The approximate mAs for exposures less than 100 milliseconds in duration can only be calculated by hand, since electronic integrators will always compute zero from the Tektronix probe output (assuming no d.c. offset). System resolution was found to be inadequate for accurate measurement of currents in the vicinity of 10 mA. Simple modifications to the P6042 system can provide capability for measuring both current and mAs over the entire range of expected exposure times.

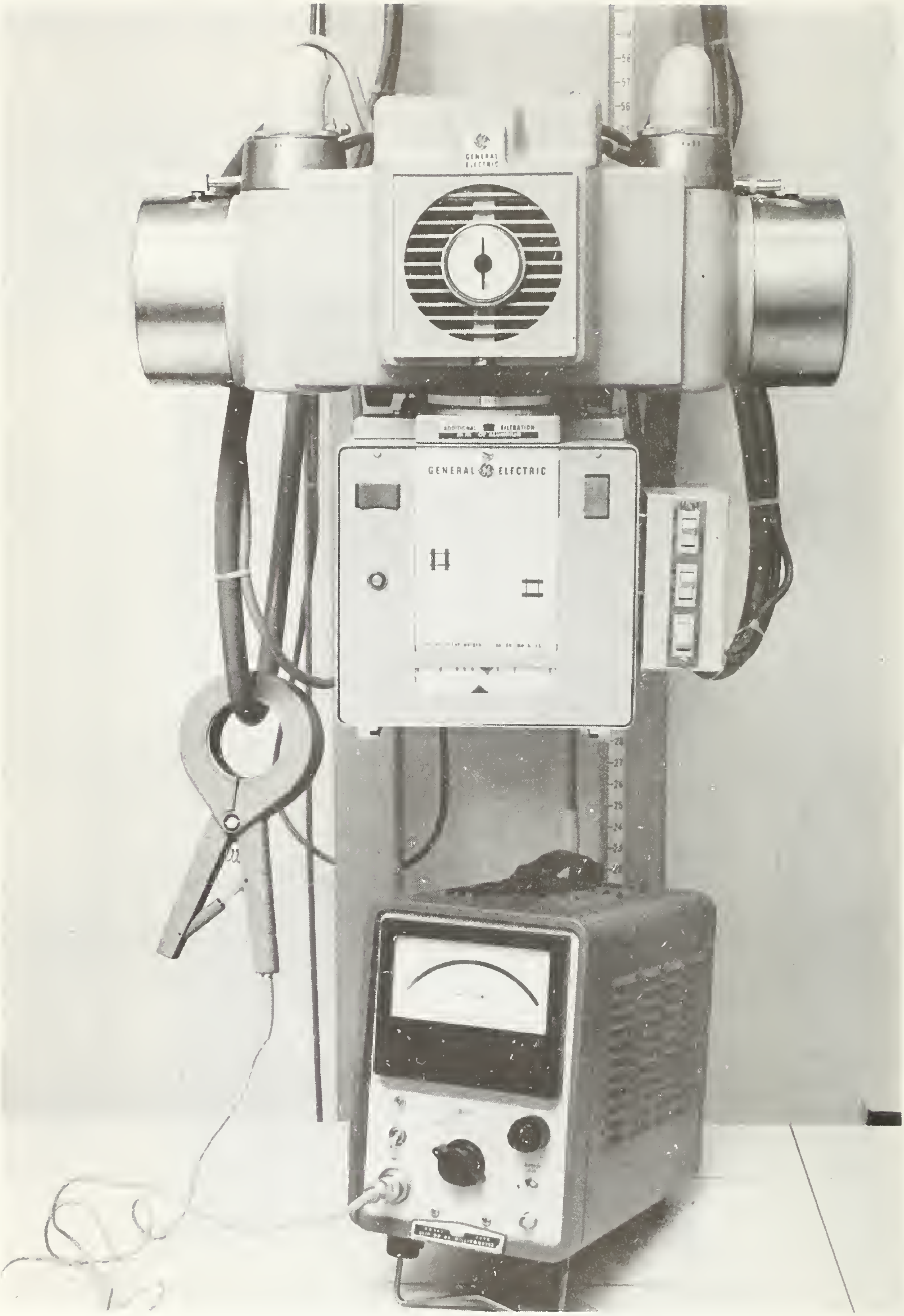


Figure 12. The Hewlett Packard Instrument.

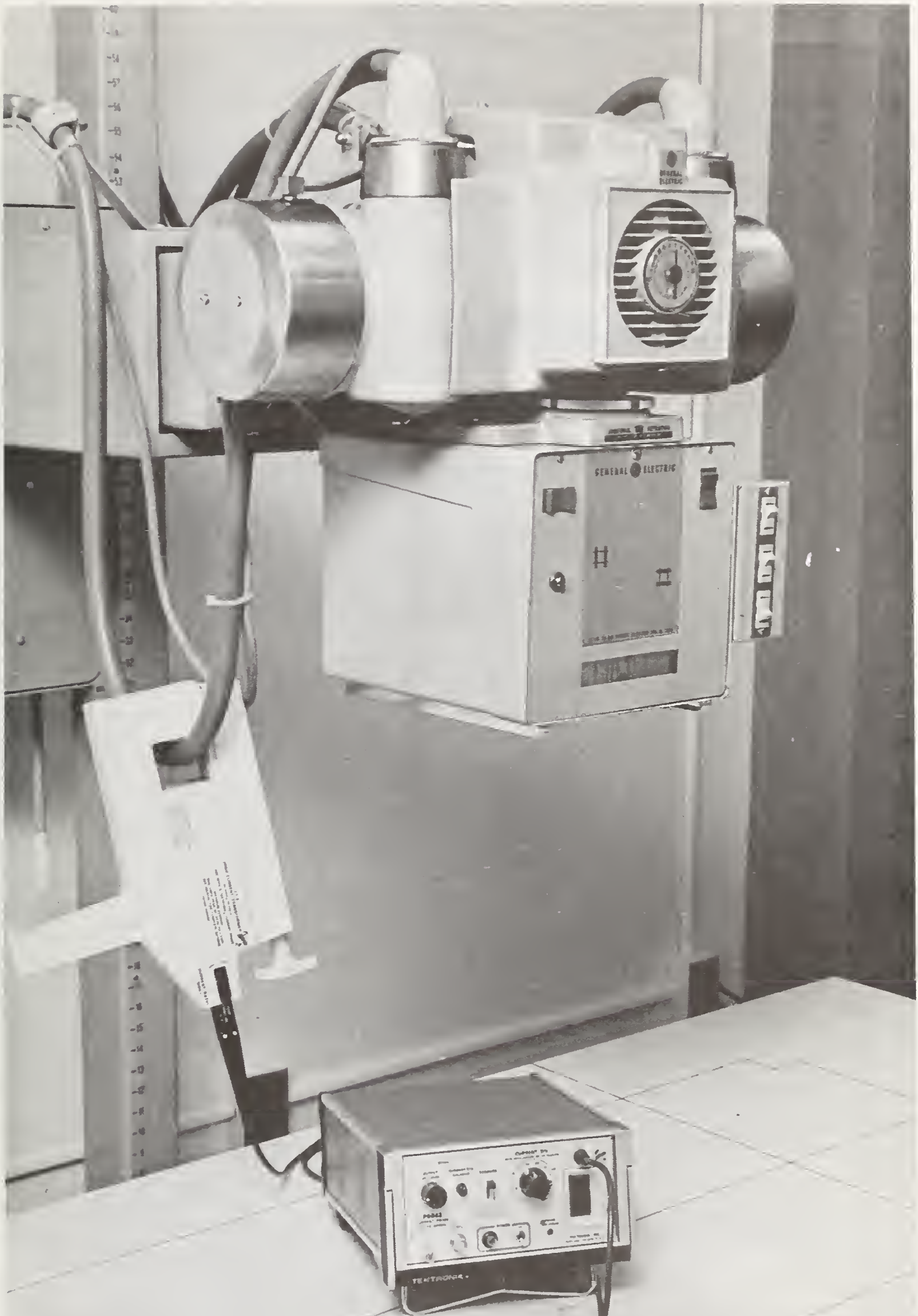


Figure 13. The Tektronix Instrument.

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(2) Cooley, J.W., P.A.W. Lewis, and P.D. Welch. The Fast Fourier transform and its applications. IEEE Transactions on Education, Vol. E12, No. 1, pp. 27-34, 1969.

(3) X-Ray Tube Current Measurements. Tektronix Application Note 60M1.0.

(4) Graeme, J.G., L.P. Huelsman, and G.E. Tobey. Operational Amplifiers: Design and Applications. McGraw-Hill, pp. 288-9, 1971.

APPENDIX A

COMPUTER SIMULATION PROGRAM

MAIN PROGRAM

```
FTN4,L
      PROGRAM FILED
      COMPLEXA(1024),G
      DIMENSION ITITL(30),ITTL(30),IYLBL(22),IXLBL(25)
     1,IXL(25),IYL(22),IT(30)
      DATA IXL,IYL,IT/25*2H   ,22*2H   ,30*2H
      DATA IXLBL,IYLBL,ITTL,ITITL/25*2H   ,22*2H   ,30*2H   ,30*2H
      IXL(1)=2HFR
      IXL(2)=2HEQ
      IXL(3)=2HUE
      IXL(4)=2HNC
      IXL(5)=2HY
      IYL(1)=2HAM
      IYL(2)=2HPL
      IYL(3)=2HIT
      IYL(4)=2HUD
      IYL(5)=2HE
      ITTL(1)=2HIN
      ITTL(2)=2HPU
      ITTL(3)=2HT
      ITTL(4)=2HPU
      ITTL(5)=2HLS
      ITTL(6)=2HE
      IYLBL(1)=2HVO
      IYLBL(2)=2HLT
      IYLBL(3)=2HS
      IXLBL(1)=2HTI
      IXLBL(2)=2HME
      TWOPI=6.283185308
      WRITE(1, 101)
  101 FORMAT(1X, "TYPE IN NTP, N, DELTA T")
      READ(1,*) NTP, N, DELTA
      DO 60 I=1,N
      A(I)=CMPLX(0.0,0.0)
60    CONTINUE
      NTR=300+NTP
      DO 50 I=300,NTR
      A(I)=CMPLX(ABS(SIN((I-300)*TWOPI*DELTA*60.0)),0.0)
      A(I)=CMPLX(1.0,0.0)
   50 CONTINUE
      WRITE(1, 102)
  102 FORMAT(1X, "TYPE IN POWER OF TWO, M")
      READ(1, *) M
      XMAX=N*DELTA
      XMAX=XMAX*1000.0
      XTICK=XMAX/5.0
      YTICK=.2
      CALL AXES(XMAX,1.0,0.0,0.0,XTICK,YTICK,IXLBL,IYLBL,ITTL)
      CALL PLOT(X,Y,1)
      DO 40 I=1,N
      X=(I-1)*DELTA*1000.0
      Y=REAL(A(I))
      CALL PLOT(X,Y,2)
40    CONTINUE
      DO 70 I=1,N
      A(I)=A(I)*N*DELTA
 70   CONTINUE
      TWOPI=6.283185308
      SGN=-1
      CALL FFT(A,M,SGN)
      AREA1=CABS(A(1))
      YMAX1=AREA1*1000.0
      YTCK1=YMAX1/5.0
      XMAX1=(N-1)/(DELTA*N*2.0)
      XTCK1=XMAX1/5.0
      CALL AXES(XMAX1,YMAX1,0.0,0.0,XTCK1,YTCK1,IXL,IYL,IT)
      CALL PLOT(X,Y,1)
      MM=N/2
      DO 10 I=1,MM
      Y=1000.0*CABS(A(I))
      X=(I-1)/(DELTA*N)
      CALL PLOT(X,Y,3)
      CALL PLOT(X,0.0,2)
 10   CONTINUE
      WRITE(6,104)AREA1
 104  FORMAT(1X,"AREA OF INPUT :",F12.4)
      DO 90 I=1,N
      FREQ=(I-1.0)/(DELTA*N)
      G=CMPLX(0.0,FREQ*2.0)/CMPLX(1.0,FREQ/.5)
      IF(I.GE.N/2)G=CMPLX(0.0,0.0)
 90   A(I)=A(I)*G
      SGN=1
      CALL FFT(A,M,SGN)
      WRITE(1,110)
 110  FORMAT(1X,"WRITE TITLE ON TTY")
      READ(1,120)ITITL
 120  FORMAT(30A2)
      WRITE(1,111)
 111  FORMAT(1X,"ENTER YMAX, YMIN")
      READ(1,*)YMAX,YMIN
      CALL AXES(XMAX,YMAX,0.0,YMIN,XTICK,YTICK,IXLBL,IYLBL,ITITL)
      CALL PLOT(X,Y,1)
      DO 80 I=1,N
      A(I)=A(I)/DELTA
      X=(I-1)*DELTA*1000.0
      Y=REAL(A(I))
      CALL PLOT(X,Y,2)
 80   CONTINUE
      CALL CRTPT(77777B,35B)
      CALL CRTPT(3,3)
      WRITE(1,200)
 200  FORMAT(2/)
      END
      END$
**** LIST END ****
```

FAST FOURIER TRANSFORM SUBROUTINE

```
FTN4,L
         SUBROUTINE FFT(A,M,SGN)
         COMPLEX A(1024),U,W,T
         N=2**M
         NV2=N/2
         NM1=N-1
         J=1
         DO 7 I=1,NM1
         IF(I.GE.J) GO TO 5
         T=A(J)
         A(J)=A(I)
         A(I)=T
 5       K=NV2
 6       IF(K.GE.J) GO TO 7
         J=J-K
         K=K/2
         GO TO 6
 7       J=J+K
         PI=3.14159
         DO 20 L=1,M
         LE=2**L
         LE1=LE/2
         U=(1.0,0.0)
         W=CMPLX(COS(PI/LE1),SGN*SIN(PI/LE1))
         DO 20 J=1,LE1
         DO 10 I=J,N,LE
         IP=I+LE1
         T=A(IP)*U
         A(IP)=A(I)-T
         A(IP)=A(IP)/2
         A(I)=A(I)+T
 10      A(I)=A(I)/2
 20      U=U*W
         RETURN
         END
         END$
**** LIST END ****
```

APPENDIX B

Supplementary Oscillographs

Although the response of a current probe system can be determined with pulse inputs only, it may be of interest to note the response of the Hewlett Packard and Tektronix instruments to various other waveshapes typical of x-ray machines.

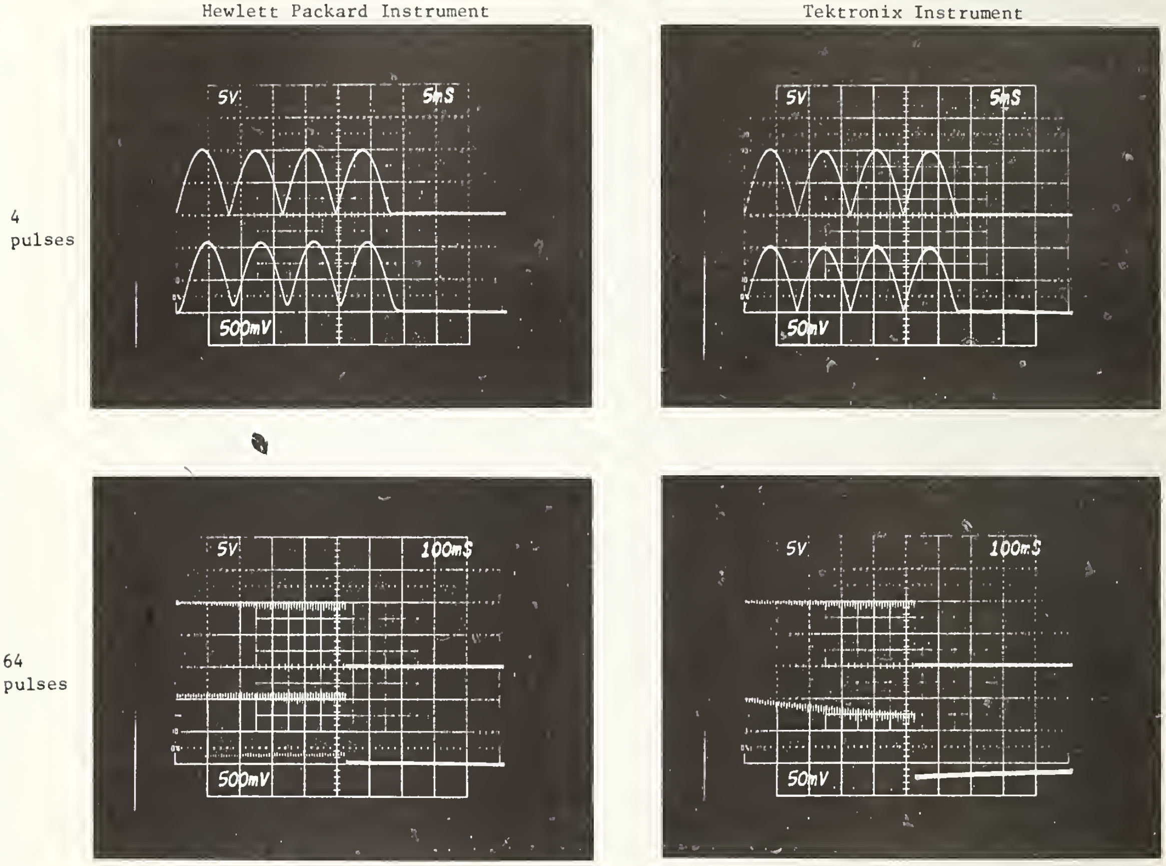
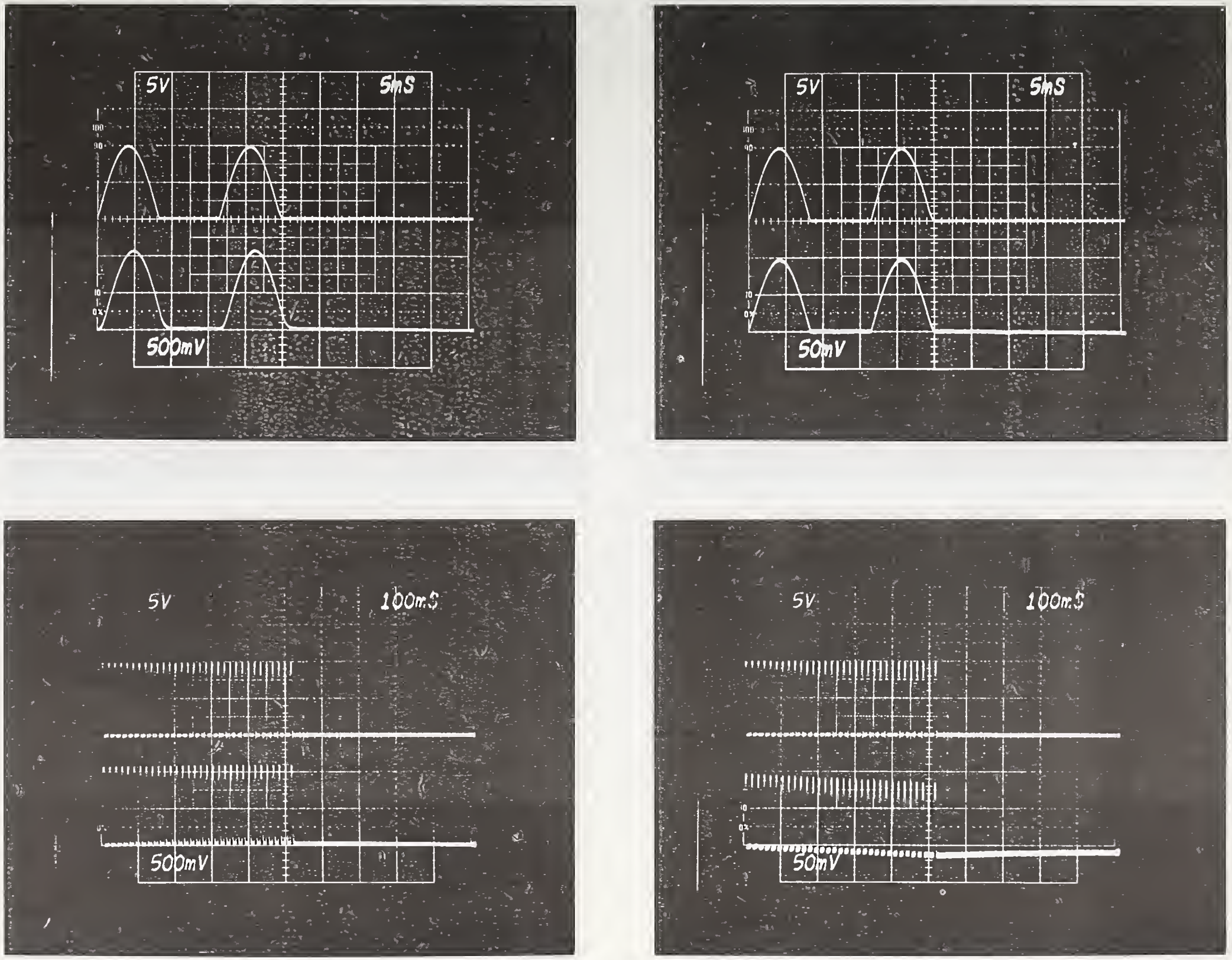


Figure 1. Response to Full-Wave Rectified Signals.



Hewlett Packard Instrument

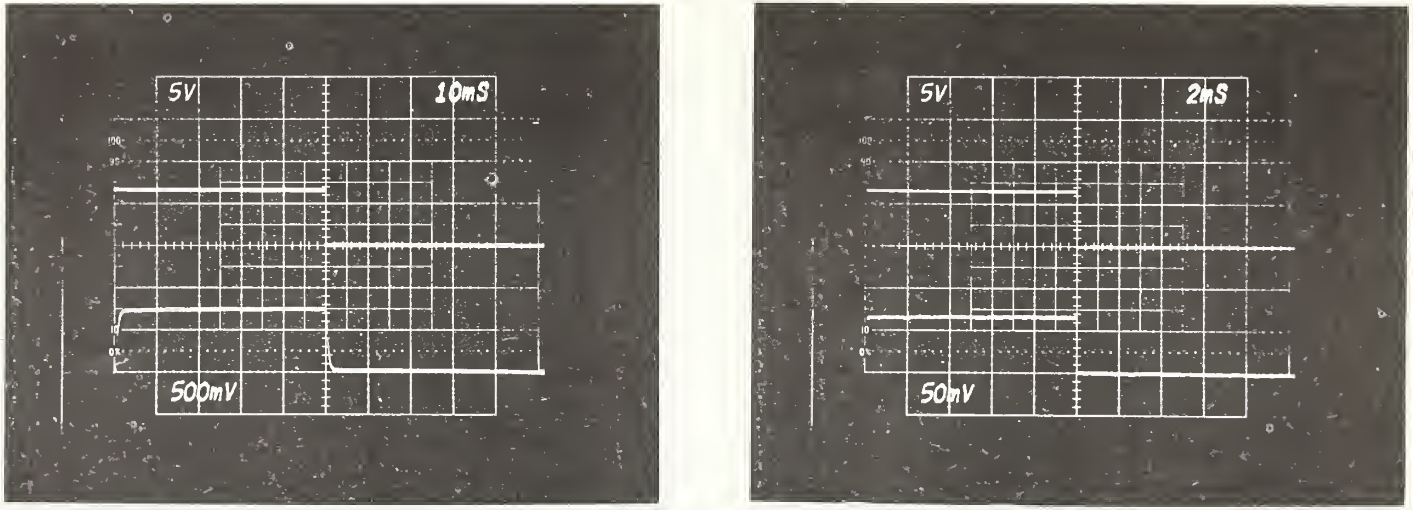
Tektronix Instrument

2
pulse

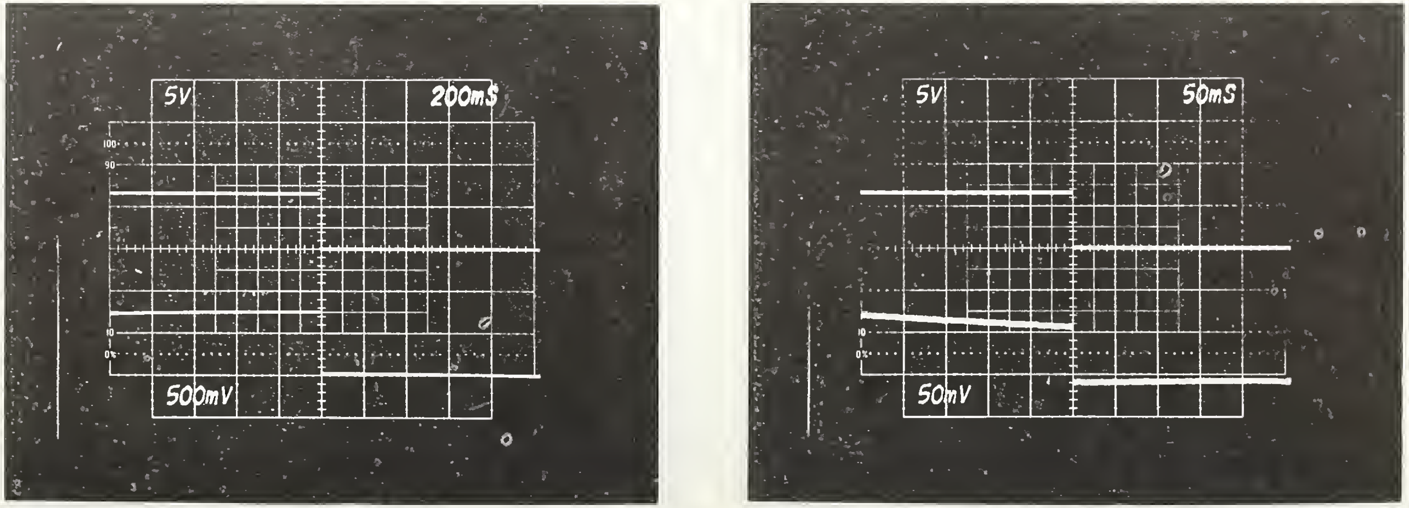
32
pulse

Figure 2. Response to Half-Wave Rectified Signals.

Hewlett Parkard Instrument　　　　　　Tektronix Instrument



50-msec pulse　　　　　　10-msec pulse



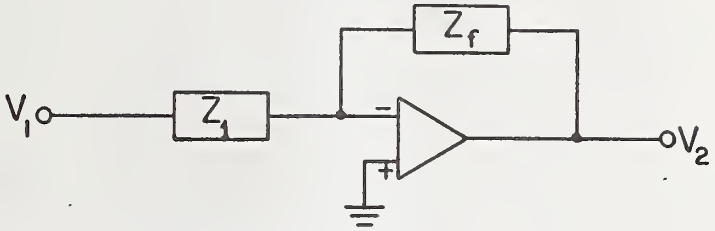
1-sec pulse　　　　　　250-msec pulse

Figure 3. Response to Forced Commutator Three-Phase Signals Not Previously Shown.

APPENDIX C

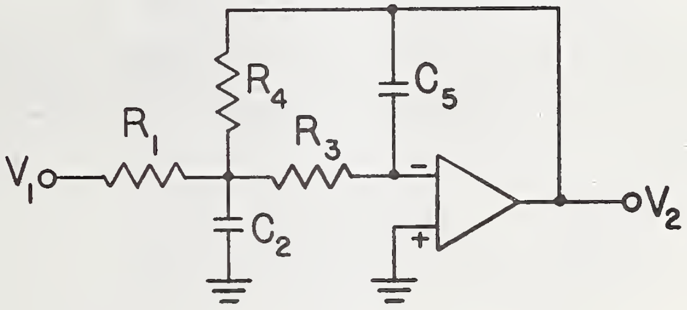
Electronic Filters

The first order electronic filters mentioned in the text were configured as follows:



where $H(s) = V_2/V_1 = -Z_f/Z_1$. In the case of the high-pass filter model for the Tektronix probe, $Z_1 = R + 1/sC$ and $Z_f = R$. Thus, $V_2/V_1 = -RCs/(RCs+1)$. For the low-pass filter of figure 11a, $Z_1 = R$ and $Z_f = R+1/sC$. Thus, for this filter $V_2/V_1 = -(RCs+1)/RCs$.

The general form for a second order low pass electronic filter is as follows *(4)*:



The transfer function of the filter is H(s), and $H(s) = -V_2/V_1 = -H_o\omega_o^2/(s^2+\alpha\omega_o s+\omega_o^2)$, where $H_o = R_4/R_1$, $\omega_o = (R_3R_4C_2C_5)^{-\frac{1}{2}}$, and $\alpha = (C_5/C_2)^{\frac{1}{2}}[(R_3/R_4)^{\frac{1}{2}}+(R_4/R_3)^{\frac{1}{2}}+(R_3R_4)^{\frac{1}{2}}/R_1]$. When two stages are cascaded as in figure 8a, the overall transfer function H(s) will be given by $H(s) = H_1(s)H_2(s)$.

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Charles J. Daniels, III, and Jeffrey L. Silberberg. A COMPARISON of INSTRUMENT PERFORMANCE in MEASURING X-RAY TUBE CURRENT and mAs.

Accession No.

U.S. Department of Health, Education, and Welfare, PHS, FDA, Bureau of Radiological Health - DHEW Publication (FDA) 76-8013 (August 1975) 27 pp. (limited distribution).

ABSTRACT: The Bureau of Radiological Health has evaluated two commercially available, noninvasive, large-aperature current probe systems for suitability in the measurement of x-ray tube current and x-ray tube current-time product as required in the enforcement of the Federal performance standard for diagnostic x-ray equipment. The response of the two systems to typical x-ray tube current waveforms is investigated and compared to the

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(over)

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KEYWORDS: Autotransformer; Diagnostic x-ray equipment; Electron beam current; Exposure; Federal Standard; Generator; Manufacturers; mAs; Operating parameters; Performance; Radiation; Transformer; Tube current; X-ray machine.

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FDA 75-8005	A Practitioner's Guide to the Diagnostic X-Ray Equipment Standard (GPO 1715-00075, $0.40).
FDA 75-8006	Report of State and Local Radiological Health Programs, Fiscal Year 1973 (GPO 1715-00074, $1.50).
FDA 75-8007	A Standard Technique for Estimating Patient Exposure from Photofluorographic X-Ray Machines (GPO 017-015-00086-9, $0.70).
FDA 75-8009	BRH Publications Index (PB 240 618/AS, $10.50, mf $2.25).
FDA 75-8010	Sixth Annual National Conference on Radiation Control - New Challenges (GPO 1715-00076, $3.70) (PB 240 984/AS, mf only).
FDA 75-8011	Radiation Control for Health and Safety Act: Consumer Protection (GPO 1712-00223, $0.25).
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FDA 75-8023	Progress in Radiation Protection 1974.
FDA 75-8024	Gonad Shielding in Diagnostic Radiology (GPO 017-015-00087-7, $0.50).
FD	elected Acoustic and Related References (PB 239-805/AS,
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FD	Health Training Resources 1975.
FD	rowave Power Density Calibration Method Using the Power niques March 1975 (GPO 017-015-00084-2, $0.85) (PB 242 ly).
FD	ry Guidelines For Diagnostic X-Ray Systems.
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FD	h Implications of Radioluminous Materials.
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FD	valuation of X-Ray Trends.
FD	of Power Density from Marine Radar.
FD	fety Handbook for Ionizing & Nonionizing Radiation.
FD	Personnel Responsible for Radiological Health Programs.
FDA 76-8007	Electronics in the Home.
FDA 76-8008	X Rays...How Safe?
FDA 76-8009	Federal/State Radiation Control Legislation 1974.
FDA 76-8010	CSU-PHS Collaborative Radiological Health Laboratory Annual Report 1974.
FDA 76-8011	Nashville Dental Project: An Educational Appr ry Improvement of Radiograpnic Practice.
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